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The Effect of Wind on Sea Level at Atlantic City

by

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Director

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THE EFFECT OF WIND ON SEA LEVEL AT ATLANTIC CITY

ABSTRACT

In a study of tidal records for Atlantic City, New Jersey, and weather maps over a period of six months, a nomogram for wind setup as a function of velocity and direction of the geostrophic wind has been developed empirically for the area.

INTRODUCTION

This study is confined to the effects of oceanic wind on sea level of an open coastline, this effect to be referred to as setup. It consists of the examination of day-to-day wind circulation over the ocean as exhibited by weather maps and the fluctuations of sea level at Atlantic City during the six-month period from November 1, 1952 to April 30, 1953. The following material demonstrates that a systematic order is achieved by the separation of the tidal data into component parts of astronomical and meteorological tide, and the correlation of wind data with an assumed wind tide. The statistical results are presented in a nomogram which gives the deviation in the height of sea level along the coast from that of the astronomical tide for all directions and strengths of winds.

The results indicate that the setup due to wind is nearly proportional to its velocity. This is in direct contrast to most observational studies which show that, in general, wind effect obeys a power law such that

$$\zeta = k\,V^2$$

in its simplest form (Hellström, 1941; Montgomery, 1938; Schalkwijk, 1947). The formula has many variations depending on its application and the region involved. A possible explanation for the contrast in results may be that most studies of the subject were either of a very general nature or were applied to confined or semiconfined bodies of water, in particular, the North Sea, Baltic Sea, Irish Sea, Japan Sea, and large lakes or semiclosed bays and not, as in this case, on an open coast where there is less possibility for land features to act as a water trap.

Setup is indicative of transport by wind currents. Various investigators have found that the slope of the sea surface is deflected to the right of the direction of wind. The angle of deflection varies for different basins, observations showing angles from 0° to 20° to the right of the wind, theory calling for as much as 45° (Schalkwijk, 1947; Doodson, 1947) with the angle between surface slope and wind direction changing slightly with velocity of wind and depth of sea.

In studies of wind effect, the influence of atmospheric pressure must be considered. It is generally assumed that the sea is in hydrostatic equilibrium with the atmosphere; thus, the state of sea level should be closely related in time to the field of pressure. Theoretically, the amount of rise or fall should be proportional to the change in pressure. For instance, a drop in atmospheric pressure of 1 cm. of mercury should be accompanied by a subsequent rise of 13 cm. of water level. Observations have shown various values of proportionality ranging from 5 to 30 cm. of water per cm. of mercury (Schalkwijk, 1947). In the case of landlocked seas and lakes, the gradient of pressure is usually insignificant, and in some endeavors it has been practical to ignore the effects of pressure on the sea.

Since setup requires distance or fetch for wind to take effect, the study also requires that one investigate not only the local wind, but wind present some distance away from the measuring station (Doodson, 1947). This leads to some uncertainty in results depending on the scale of the assumed wind field, the time lag required to reach a state of equilibrium, and the topography of the area. Other disturbing factors which may possibly influence the state of sea level and the estimate of setup are local additions such as rainfall and runoff, thermal effects and advection, oscillatory surges, and widespread effects difficult to distinguish (Montgomery, 1938).

ANALYSIS

It is a well-known fact that onshore winds will raise sea level above a predicted height and that offshore winds will lower sea level. Satisfactory studies of this phenomenon have been made by treating the two tides, the astronomical and the meteorological, as being additive without mutual disturbance. Their mutual independence is not entirely true, for, in shallow water, sea level is more affected by wind at low tide than at high tide. Also, the high and low waters of the astronomical tide are affected in some degree by the stage of sea level induced by wind. The present analysis of the tidal data does not take into account these minor objections.

The Meteorological Tide

Consider a tidal series in which the problem is to determine the most suitable means to separate perturbations directly due to astronomic influence from perturbations due to meteorological influence. The latter is assumed to represent variations by chance and embraces ALL factors not otherwise directly affected by extraterrestrial effects.

Then

TOTAL OBSERVED TIDE = ASTRONOMICAL TIDE + METEOROLOGICAL TIDE

If a TIDE is predicted for a given place with the use of the major astronomical constituents, then, the difference between predicted and observed tide represents the meteorological tide. Objections to this method are that it restricts the application to places where predictions are available, and, that the predictability may not be entirely adequate, especially where shallow water effects alter the constituent tides.

An alternative method for the elimination of the astronomical tide is suggested by the calculation of instantaneous sea level which, in its simplest form, consists of an averaging process of 24 successive hourly heights of tide (Marmer, 1951) centering about the time in question. Doodson and Warburg (1941) suggest a particular averaging combination spanning 38 hours which is very effective in filtering out both the lunar and solar short-period constituents. Since the major long-period tidal constituents are usually of small consequence, the latter method was adopted in this study.

The tidal observations and published predictions for the primary tide station at Delaware Breakwater provided an excellent opportunity for comparison of the two methods. The Doodson method applied to the observations gave instantaneous heights of sea level for any hour. Since the predictions are based on a datum of mean low water which, in turn, is fixed relative to mean sea level, the difference between observed and predicted heights of tide should, also, give the instantaneous heights of sea level, providing the predicted times of high or low waters are accurate. Thus, both types of calculations are ways to obtain departures from mean sea level. For 235 observations of high and low waters the calculated standard deviation was 0.16' or 2% of the tidal range. The correlation coefficient between the two methods was 0.985 +/- .0034.

It is worthy of note that the Doodson method was apparently successful in eliminating the higher harmonics of the shallow water constituents. The process demonstrated smooth curves, indicating no regular perturbations, when it was applied to Philadelphia data; this station lies 100 miles upstream from the mouth of Delaware Bay. In spite of the fact that long-period astronomical variations were not filtered out by the Doodson process, it was evident, from the above results, that this method was useful for determining the meteorological tide.

The Barometric Pressure Correction

Weather data showed that it was possible, theoretically, for the tide to rise or fall as much as 1/2 to 3/4 foot with

the variation of atmospheric pressure alone. Direct observations of the pressure effect on sea level were impractical, but, with a few assumptions, it was possible to achieve a rough estimate.

In the first place, there was no assurance that the water level responded consistently to the immediate overhead pressure. Consequently, the pressure field over a considerable area was considered rather than the pressure at the station itself. Secondly, it was assumed that, when the wind was light and variable for a reasonable duration, the meteorological effect was primarily induced by barometric pressure (Schalkwijk, 1947).

The pressure field was measured about a circular area 300 miles in diameter centering about 38°N. Latitude, 72°W. Longitude (Fig. 1). The field includes Atlantic City at its circumference and covers most of the ocean surface that might be presumed to affect sea level at that station (Fig. 2). Weather maps for the period of observation were examined for slow-moving cells and small pressure gradients indicative of intervals of little surface wind circulation. Also, the meteorological tide was examined for intervals of apparent equilibrium. In the six-month period there were 18 instances during which periods of little wind coincided with periods of stationary meteorological tide. With these data it was found that the correction applicable to the meteorological tide at Atlantic City was -1 cm. per millibar. The barometric datum for these corrections was 1016.5 millibars, annual mean sea level pressure for the area.

The excellent agreement with the theoretical value was obtained by averaging eight pressures about the circumference of the circular area and correlating these averages with the departures from mean sea level, the meteorological tide. Comparison of these values showed a negative correlation of 0.824 with a probable error of 0.054. A line of regression demonstrated a slope of 29.1 millibars per 30.5 cm. or one foot change in sea level.

The Wind Tide

Setup has been defined as the effect of wind upon sea level. The term should not be confused with the somewhat synonymous term, "windstau", or wind effect. The latter word lumps the barometric effect with the effect due to the tangential stress of wind. Windstau can be loosely applied to the meteorological tide; however, setup is a further refinement requiring the elimination of the effects of atmospheric pressure. With this done the way was clear for investigation of the wind tide, the fluctuations of sea level assumed to be due to wind alone.

In the following discussion, wind directions and velocities refer to the <u>geostrophic wind</u> paralleling the isobars at the sea surface. In lieu of direct observations over the wide oceanic

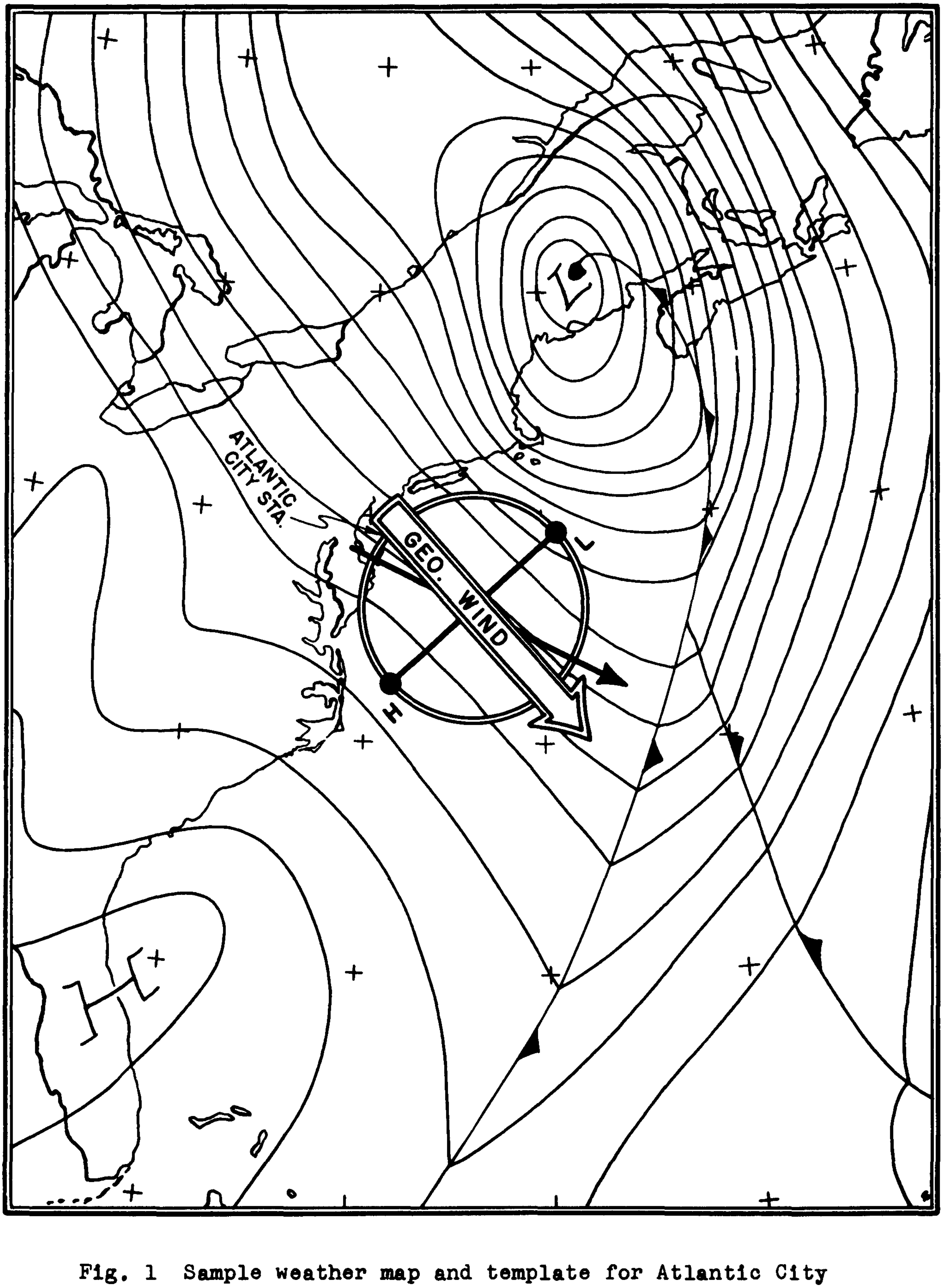


Fig. 1 Sample weather map and template for Atlantic City

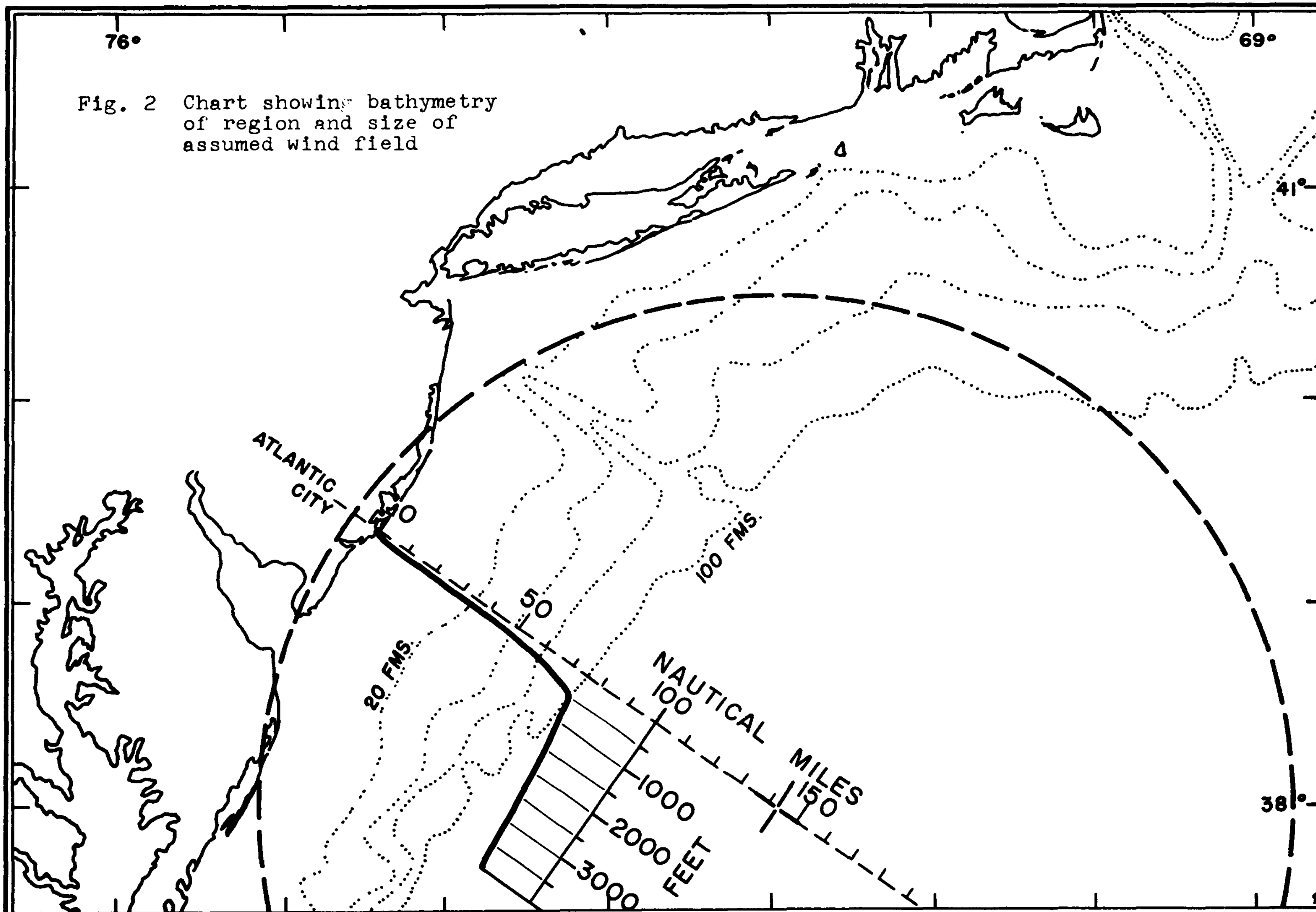


Fig. 2 Chart showing bathymetry of region and size of assumed wind field

area concerned, the estimated geostrophic wind has been used to indicate the strength and direction of the wind at the sea surface. The relation of actual wind over the sea to the geostrophic wind is generally fairly simple, with a ratio between observed and geostrophic winds of 2:3 (Petterssen, 1940). The direction of observed wind in middle and high latitudes varies from 15° to 30° to the left of the isobars (northern hemisphere). An approximate relation of 20° to the left of the isobars was adopted for the study area (Chase, 1951).

Pressure fields of daily (0730 EST) weather maps were examined and the main pressure gradient across the 300-mile circle was noted for each map (Fig. 1). Direction was recorded by taking a line normal to the tangent of the isobars and directed towards high pressure ($L \rightarrow H$). Geostrophic wind is 90° to the left of this line. In some cases direction was somewhat uncertain owing to the excessive curving of isobars within the field. The uncertainty is further complicated by the relation of actual wind to isobaric curvature (Petterssen, 1940). For convenience, the direction and slope of the pressure gradients were used as parameters of wind velocity.

To determine the time lag between wind and setup, the daily pressure gradients were compared with various heights of meteorological tide. It was assumed that if these heights were sorted according to wind directions, or directions of high pressure, a rudimentary sine wave should be demonstrated. Furthermore, it was assumed that this sine wave should show greatest amplitude when a delayed interval of time between wind and tide corresponded with the unknown time lag. Heights of meteorological tide, corrected for barometric pressure, were tabulated at six-hourly intervals (t + 0, t + 6, ... t + 24 hrs.) for each weather map. Each group was plotted separately against wind direction and summed vertically for harmonic analysis. Successive harmonic analyses for the five probable time lags showed a convergence with greatest amplitude at t + 12 hours. It became apparent that, if wind tide was the predominant constituent of the meteorological tide, a general delay of 12 hours was required for sea level to reach an equilibrium with given large-scale wind forces.

Once the time lag was determined, it was an easy matter to find the relation between sea level and wind. In order to obtain the characteristic setup for the locality it was desirable to have numerous wind data for all directions and velocities. Figure 3 shows near fulfillment of this condition. The figure gives the percentage occurrence of geostrophic winds both for velocity and direction during the period of observation. All directions are represented but not evenly distributed; northwesterly winds were prevalent and southeasterly winds were deficient. Velocities up to Beaufort 11 (22 millibar gradient) were recorded with marked prevalence of winds from Beaufort 4 to 6.

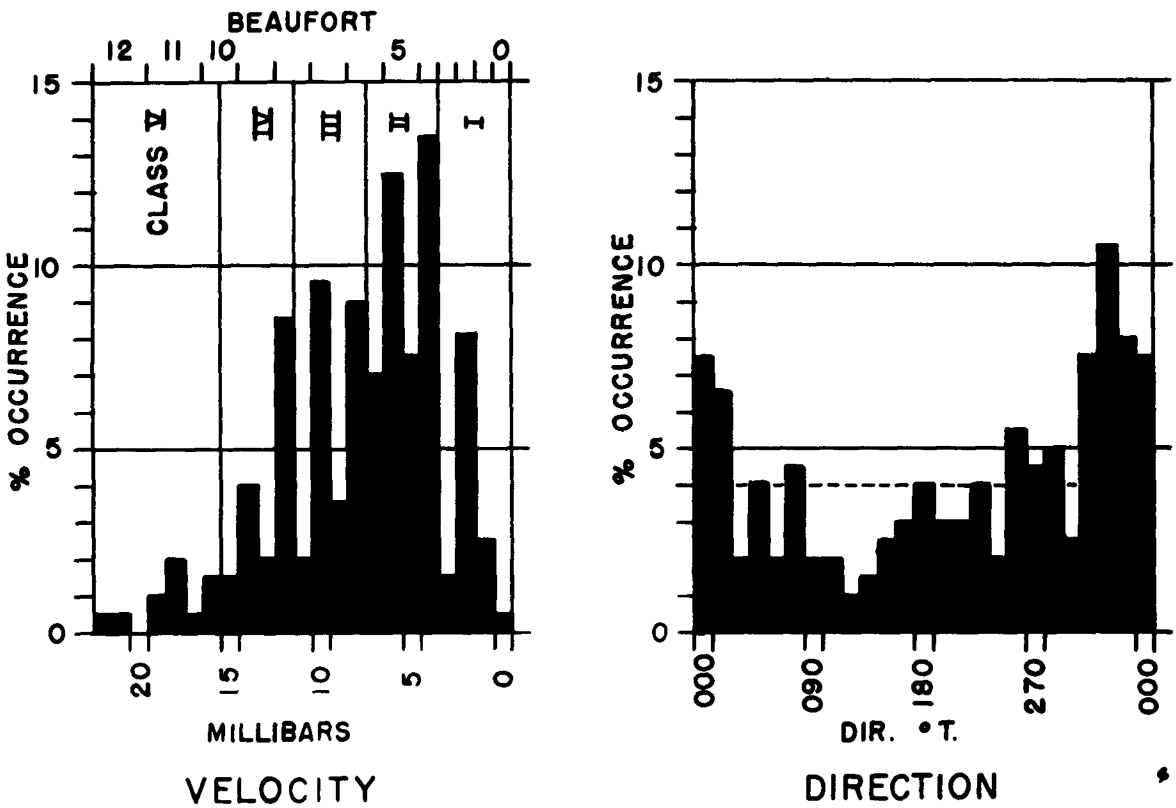


Fig. 3 Percentage daily occurrence of geostrophic winds for sea level pressures off Atlantic City from November 1, 1952 to April 30, 1953. (Note class distinctions for wind velocity used in claculating wind setup).

As shown in Figure 3, the daily geostrophic winds were separated in five classes of velocity. The classifications were sufficiently broad to include full directional distribution within each class. Class V was not complete in the latter sense; however, water levels associated with these maximal winds were more certain than any other class. In each classification, an harmonic analysis was made for the assumed wind tide versus direction of high pressure on the simple assumption that a symmetrical sine wave should express the relation between sea level and direction for winds of any given velocity.

The results of these analyses are shown in Figure 4 which gives the calculated sine waves for each class of velocities. These curves relate sea level in terms of the tide staff at Atlantic City with wind as indicated by direction of high pressure. The observations for Class III are shown in the diagram as open circles. There is considerable spread of these observations about the curve; consequently, the curves are exact only to the extent in which harmonic analysis is appropriate. These curves were derived by averaging appropriate intervals for 12-ordinate or 6-ordinate analysis and were reconstructed with the calculated phases and amplitudes. It was evident from the consistent phase lag and progressive amplitudes of the curves that the assumed wind tide was predominantly wind setup.

APPLICATION

The figure of wind setup as a function of wind force (Fig. 4) was derived by a series of analytical steps, none of which could be considered a precise evaluation. Consequently, the figure represents a statistical result which is weighted by the limitations of the data. For example, the curve representing the least wind class (Class I) is inordinately large in amplitude because of winds bordering the next highest class (Fig. 3) and the probability of a nonexistent state of equilibrium (12-hour lag). Thus, the roughness of the figure permitted a limited amount of smoothing with respect to increasing velocity and setup.

In order to apply these results to the detailed observations and to test their usefulness with independent data, a nomogram was constructed from Figure 4. In its construction, smoothing was mainly confined to the least wind force class which, because of its nature, contained the most ambiguous set of points. Lines joining opposing directions (such as 090° and 270°), in an intermediate graph of velocity versus setup, intersected at a point in the graph corresponding to 6.68' on the Atlantic City tide staff and zero velocity. The convergence to the null point, 6.68', was important, for it established an arbitrary datum which was interpreted as being mean sea level for the period in the absence of wind.

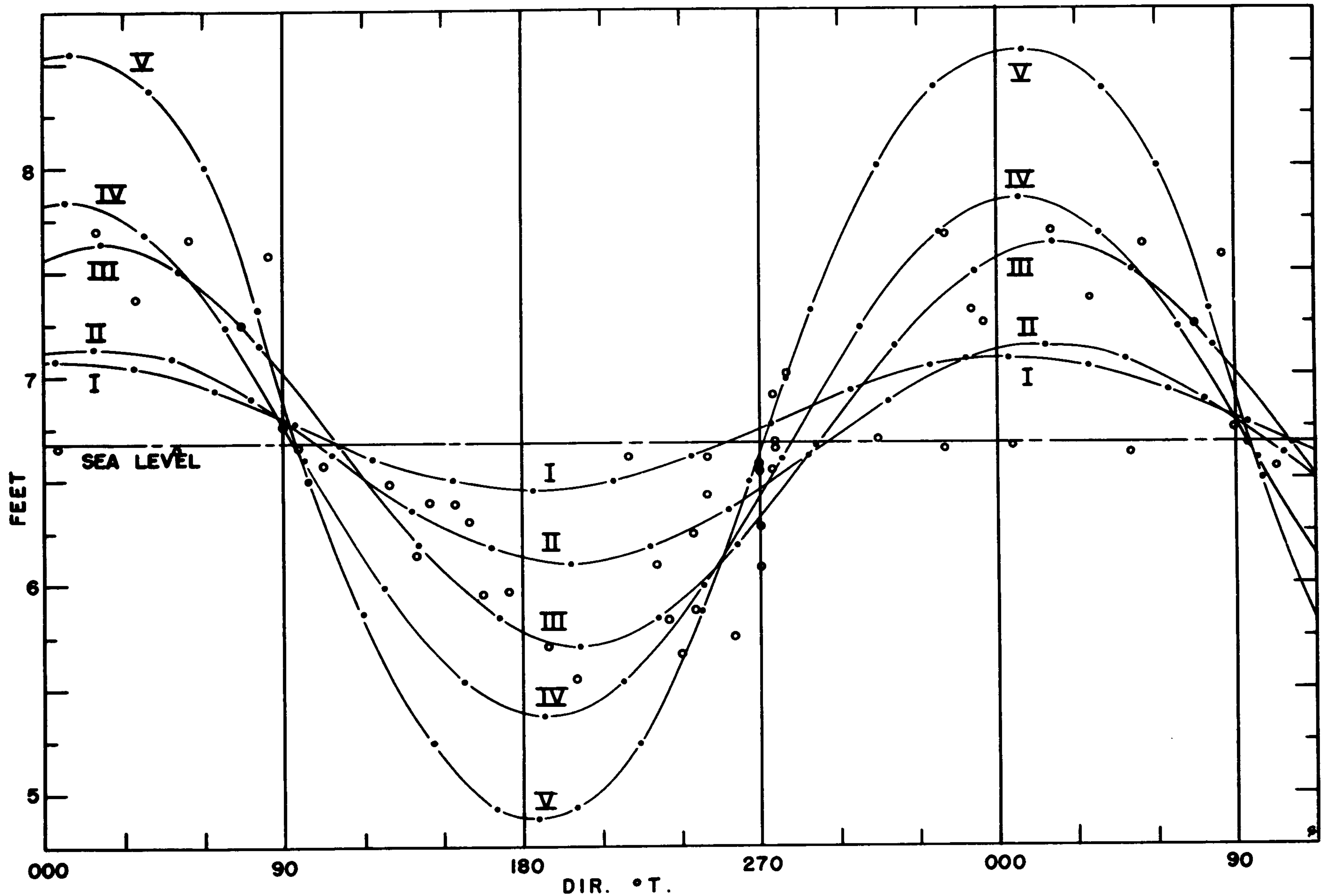


Fig. 4 Results of harmonic analyses for various class strengths of wind velocity referred to the tide staff at Atlantic City

The nomogram is shown in Figure 5. It consists of a series of isovelocity lines, pressure gradients, about a polar coordinate system. When a vector directed radially in a given wind direction intersects the given wind velocity line, the amount of setup is indicated by the radial scale. The large figures in the diagram refer to the direction from which the geostrophic wind may blow, while the smaller figures give the direction of high pressure. For reference, the dashed line passing through the diagram shows the orientation of the coastline at Atlantic City.

When no wind is present, the sea surface, neglecting barometric pressure differences, is shown by the circle marked Sea Level. Extreme wind velocities demonstrate a cardioid figure superposed over the circle; the apex of the figure shows a minimum sea level; the opposite direction, a maximum. It is readily apparent that the greatest deviations of sea level occurred when the geostrophic wind was blowing from 100° and 280° True (010° and 190°, directions of high pressure). Wind at right angles to the above did not show a definite null effect on sea level at Atlantic City. Depending on the velocity of the wind, the effect, for example, from 010° True, with increasing wind, was at first, a depressing of sea level and then, with higher velocities, an elevation. With wind from 190° the effect was reversed. The nomogram demonstrates particular sensitivity about the latter directions.

The application of the nomogram to hindsight prediction of the tides at Atlantic City for the period of study, using a 12-hour time lag, showed good correlation with the observed meteorological tide. Figure 6a shows the meteorological tide, corrected for barometric pressure, for the entire six months of observation. The calculated wind tide or setup is indicated by black dots. Sea level in the absence of wind is shown by the straight line at 6.68'. The compressed horizontal scale exaggerates the discrepancies, but an expanded scale shows how well the calculations agree with the observations. Figure 6b represents the January portion of Figure 6a, where the dashed line shows the meteorological tide and the full line the same tide corrected for pressure.

Monthly correlation coefficients for the calculated and observed wind tides were greater than 0.80 except for those of January and February which were somewhat less. A much improved correlation was achieved by the elimination of periods when weather maps showed local pressure cells centered in the measuring area. Probably the lag required to reach equilibrium with these local winds was less than 12 hours; it is also probable that the limited fetch produced a setup less than that indicated in the nomogram. Measurements involving these local cells were further complicated by the departure of the actual from the geostrophic winds due to the extreme curvature of the isobars.

The nomogram was applied to an independent set of data to determine its relative usefulness. Cape Henlopen, at the

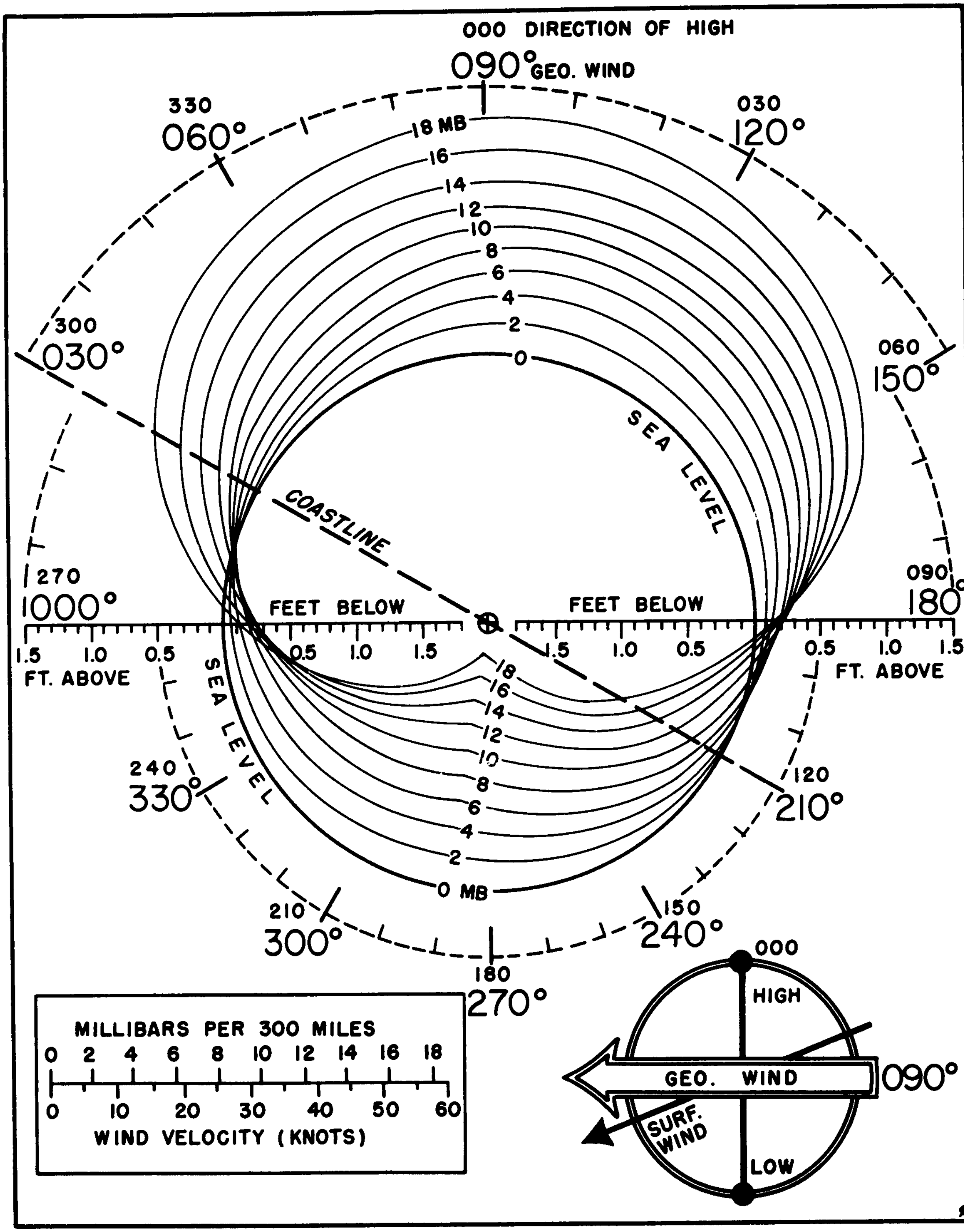


Fig. 5 Nomogram for wind setup at Atlantic City. The foot scale may be oriented to the proper wind direction to find the expected setup 12 hours following the observation. Allow for barometric pressure at time of setup.

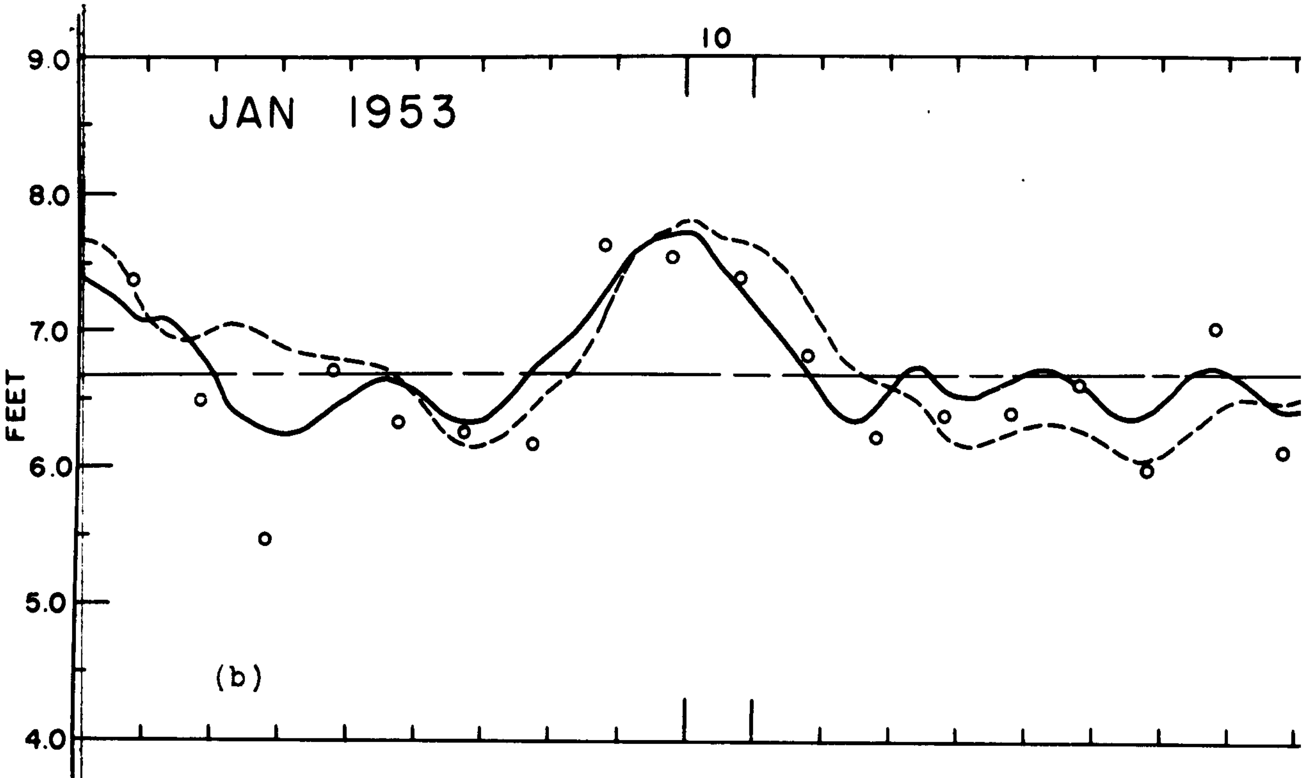
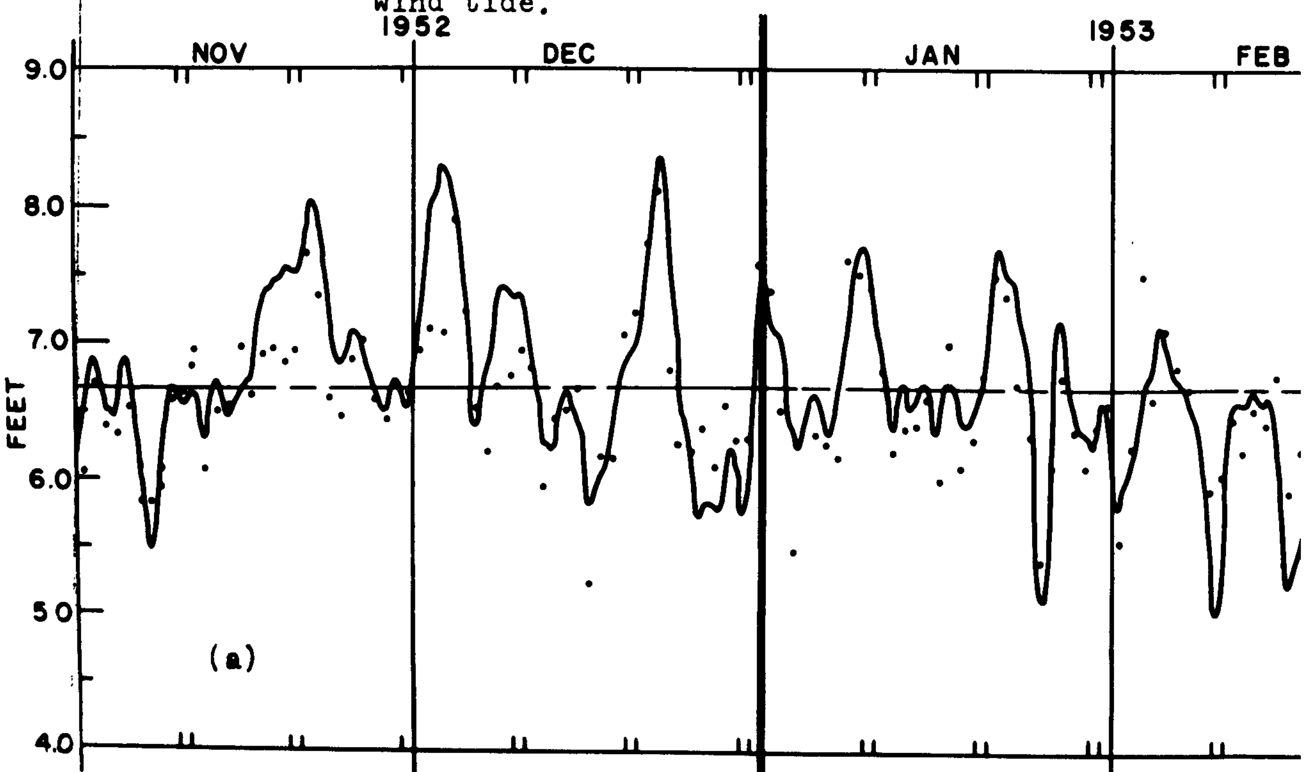


Fig. 6a Meteorological tide during the six months of observ
and points indicating the calculated wind tide.

6b Meteorological tide for January expanded to show th
wind tide.



entrance to Delaware Bay, is not far distant from Atlantic City, and the surrounding coastline is more or less similarly oriented, aside from the fact that one might expect dissimilar features due to the Bay itself. Easily accessible tidal predictions and observations suggested this station for evaluation of the nomogram.

A relation was found between the tide staffs at Fort Miles (Cape Henlopen) and at Atlantic City to establish a working datum. After a correction was applied for the difference in tide staffs, weather maps and the nomogram were used to determine a wind tide, the setup, for October, 1952 (See Fig. 7a). Since tidal predictions are based on the mean low water of the locality, it was necessary to restate these predictions in terms of the tide staff. Predictions of high and low water were also revised according to the calculated wind tide with allowances for barometric pressure. Thus, three sets of high and low water figures, in terms of the tide staff at Cape Henlopen, were obtained for the month of October, 1952, the predicted tide, the observed tide, and the predicted tide corrected for wind effect.

The normal and revised predictions were compared with the observed high and low waters. Considerable improvement over the astronomical predictions was noted when wind and pressure was allowed for, as shown in the correlations below.

Correlation Coefficients between
Observed and Predicted Tides

	High Water	Low Water
Astronomical Predictions	0.605 +/- 0.048	0.794 +/- 0.032
Revised Predictions (Corrected for Wind and Pressure)	0.872 +/- 0.021	0.947 +/- 0.009

Figure 7b shows that in spite of the improved correlations, differences as much as 1/2 foot occurred. This figure is a graph of the difference between the revised tidal predictions and the observed tides (open circles represent Low Water and black circles High Water). Except for three or four discrepancies, these differences were systematic. Most of the systematic deviations are accounted for in the difference between the calculated and the observed meteorological tide which is plotted on the graph (dotted line). Thus, if the calculated wind tide were ideally correct, the revised predictions should show nearly complete agreement with the observed tide.

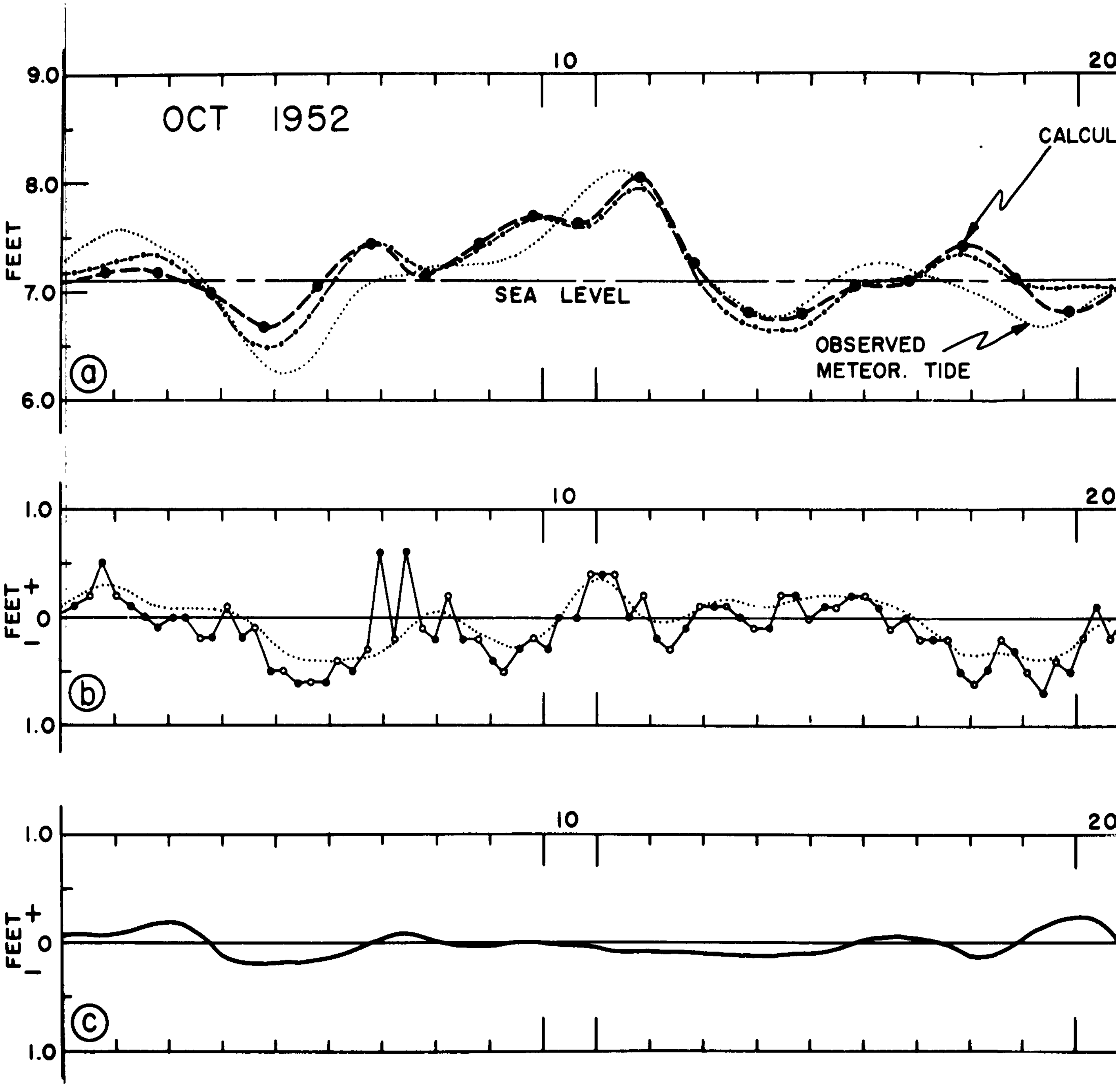


Fig. 7 Calculated and observed tides for Cape Henlopen (October 1

a) Curves showing the calculated wind tide -●--, the wind ti -•-•-•, the observed meteorological tide .....
b) Difference between predicted tide (corrected for wind and tide: (•- High Water), (o- Low Water).
c) Calculated barometric pressure effect.

DISCUSSION

The preceding analyses show that a major part of the discrepancies between the predicted heights and actual heights of tide can be accounted for by wind setup induced by an adjacent oceanic wind field over a fairly wide area. The range of wind tide at Atlantic City is comparable to that of the astronomical tide, while the effect of barometric variation, being much less, is still of sizable importance.

The effectiveness of the nomogram should be judged in a statistical sense and not in individual application. The strict adherence to a 300-mile geostrophic wind field and a 12-hour time lag will not account for all the wind forces; it merely serves as a statistical tool which is perhaps most effective where the wind field is nearly homogeneous and not changing too rapidly. The fact that the derived setup applies to an open coast location permits a variety of casual conditions for anomalous results which might be lessened were the location protected by land features.

With regard to its statistical derivation, it is surprising that so much consistency remains in the analysis. For instance, if we apply the mean direction and velocity of the wind for the 6-month period in the nomogram, we obtain a figure of 6.55', which is the figure derived by averaging all the hourly heights for that period.

In the introductory portion of this paper it was pointed out that most investigators have found that wind setup was more or less proportional to the square of wind velocity. Although wind, in this study, was measured in units of pressure at sea level rather than actual surface velocity, the above rule seems to apply only to longshore directions of wind. For most directions, the relationship between setup and wind velocity is nearly linear.

Examination of the nomogram clearly shows the angle of deviation between maximum setup and wind. The coastline bears 030°-210° True. If we assume that maximum setup can only occur when the net transport of water is normal to the coast, the nomogram shows that, for given wind velocity, greatest setup occurs when the geostrophic wind blows from 100° or 280° True, that is, 20° to the right of the normal. We can also assume that if sea level at Atlantic City is unaffected by wind, neglecting gradient currents, the net transport of water normal to the coastline should be zero, that is, parallel to the coastline. The nomogram shows that this latter condition is fulfilled where the isovelocity lines intercept reference Sea Level; the angle varies between 13° and 25° to the right of the coastline.

According to Rossby and Montgomery (1935), the angle of deviation between surface wind and gradient wind for the latitude of Atlantic City should be about 20° in the case of an

4. The application of the nomogram to the set of data showed good monthly correlations with observed tides. Further applications to tidal predictions for Delaware Breakwater showed marked improvement over normal predictions when compared with the observed high and low tides.

5. Maximum setup for the open coast at Atlantic City suggests a linear relationship with velocity, deflection of the water slope oriented approximately 40° to the right of the direction of surface wind, and a general time lag of 12 hours to reach equilibrium with the wind force.

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